EVS24
Stavanger, Norway, May 13-16, 2009

Urb-e: ENEA project for a low consumption urban vehicle

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Abstract

In 2006 the Hybrid and Electric Research Group of ENEA planned the realization of an hybrid powertrain suitable for small city car (“quadriciclo leggero” for Italian homologation rules) able to fulfil the 350 kg limit for the overall vehicle weight (comprehensive of storage system) imposed by legislation.

To fulfil the project, ENEA asks to Sapienza University of Rome to collaborate to the project for the i.c. engine optimisation, rolling chassis design, and hybrid powertrain control, and to University ROMA TRE to collaborate for the electric machines and converters.

The main targets of the project, called “Urb-e”, are to realise a powertrain able to achieve low fuel consumption (2.5 litre/ 100 km), low emissions (comparable to EURO 5 rules), together with simple configuration and low powertrain cost.

Keywords: series HEV, ULEV, ICE,EDLC.

1 Introduction

Urb-e is a light weight vehicle dedicated to an urban use and the hybrid powertrain will be realised in series configuration; the traction will be totally electric and the electrical energy generation will be fulfilled by a special auxiliary power unit. An energy storage system will be present in order to perform the regenerative braking mode and in order to isolate the energy generation device from the actual energy needed for the traction.

Thus, as usual in series hybrid powertrain, the auxiliary power unit (APU) can be operated almost independently from the dynamic requests of the vehicle.

The storage system operates as a energy tank between traction motor and APU and its capacity of store energy will be a fundamental parameter for the APU management.

Thus considering, the main original aspect of the project here presented is represented by the kind of energy storage technology that will be adopted; in fact, in order to achieve the goals of a light weight powertrain and a great cycle life of the storage system, the ultracapacitor technology has been chosen for the storage system.

That choice will have a great impact on the powertrain sizing and on the system management strategies; in fact the ultracapacitor technology is characterised by advantages and disadvantages [1][2] respect traditional battery solution (see Tab.1).

Thus considering with ultracapacitor cells it is possible to made up a storage system light, powerful, simple to monitoring and able to perform an optimal regenerative braking phase [3]; all that favourable characteristics are very interesting for our application, but on the other side that advantages are accompanied by low overall energy capacity and complication due to the high voltage variation rate that can be a problem for the electronic inverter of the traction motor. The problem of the high voltage variation rate will be solved with an electronic device called

Voltage Booster and will not be discussed here; the second problem, the low overall energy of the storage system, will be one of the main parameter to be assumed for the APU design and management and will influence greatly the management strategies of the APU.

Table 1: Ultracapacitor technology

Advantages	*Disadvantages*
High specific power (4-5 kW/kg)	Low specific energy (5-6 Wh/kg)
High power density (1.5-2 kW/litre)	Low energy density (8-10 Wh/litre)
High life cycles (500'000 – 1'000'000 cycles)	Great voltage variation under operation
Simple state of charge evaluation	
Charge and discharge symmetrical behaviour	
High efficiency	

In particular, with a low energy storage system, the fixed steady state APU operation (typical of series hybrid) will be not viable and satisfactory [4].

2 Powertrain layout

The ENEA project for a small city car with low fuel consumption and good performances has been defined considering the general targets reported in tab.2. In order to meet those targets a series hybrid powertrain layout with ultracapacitor storage has been choose; the series hybrid powertrain has been preferred for its simple layout and low cost in comparison with the parallel or power split configurations.
In fig.1 the configuration of the system is reported. The generator set, composed by i.c. engine and electric generator, is placed in the rear of the rolling chassis; the storage system is positioned between the two sets and the rear firewall, together with the CPU dedicated to the system management. The traction is on front wheels and is performed by an electric motor equipped with a one speed mechanical transmission with

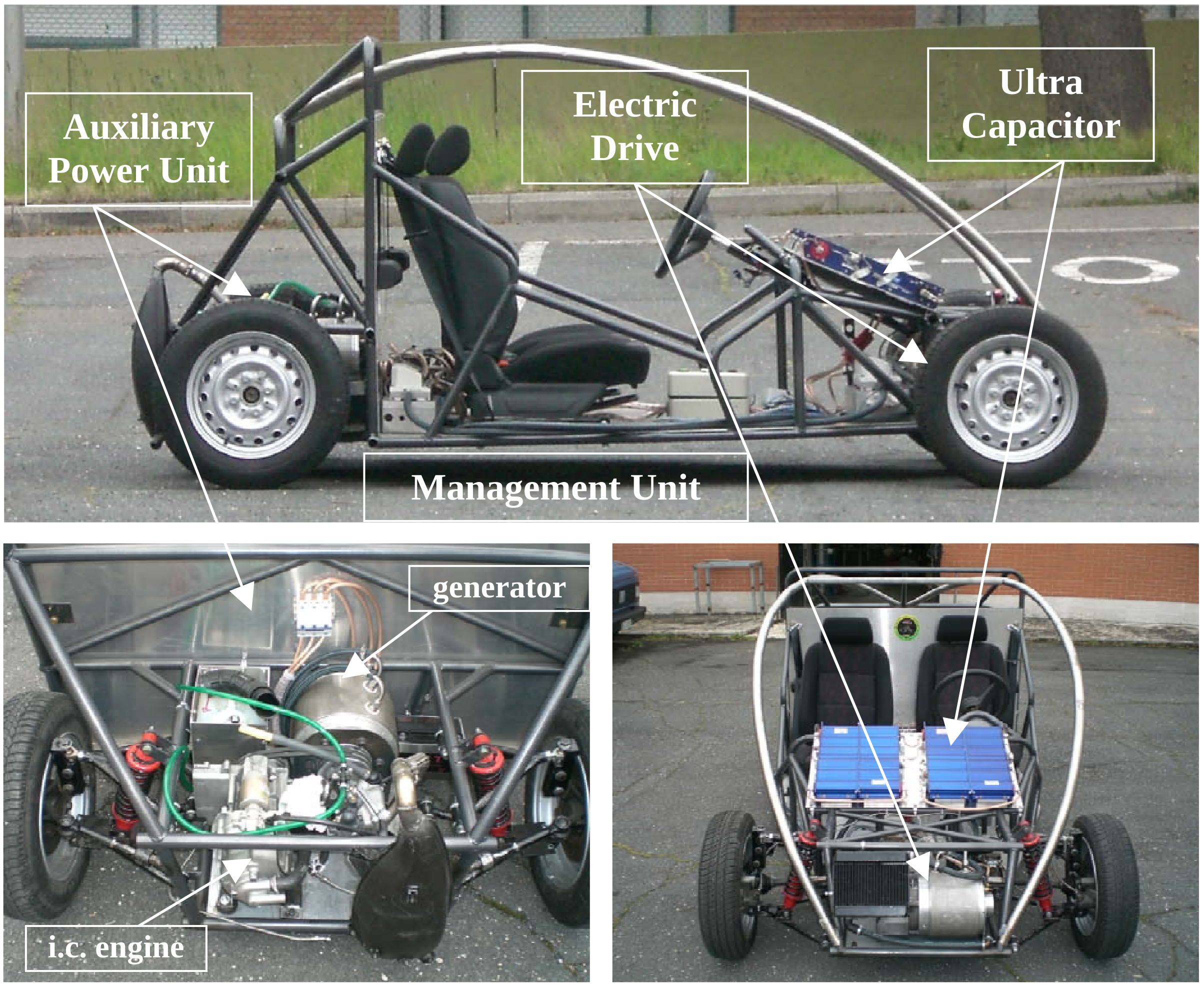

Figure 1. Urb-e powertrain layout.

differential. A two motors (one for each driving front wheel) configuration has been considered, but costs considerations suggested to adopt the single motor layout.

Tab.2. Powertrain general targets to be achieved

Total vehicle weight	<350 kg
Max acceleration rate	>1.4 m/s^2
Top speed	>70 km/h
Max climbing angle at top speed	>4%
Max climbing angle	>17%
Fuel consumption (ECE 15))	<2.5 l/100 km
Emission level	EURO 4

In order to realise a light, modern and efficient generator set, an i.c. engine unit derived form the scooter market has been considered; in tab.3 the main i.c. engine specifications are reported.
The max power output is higher than the power needed for the generator set, but, considering that it is achieved at a high revolution speed (8500 rpm) that will not be utilised in the generator set for noise emission reasons, the choice of a less powerful engine has been rejected; in fact, the characteristics of lightness, emissions level and overall engine design quality warranted by this 250 cc engine are not typical of smaller engines, in many cases less sophisticated and efficient.

Tab.3. I.C. engine main specifications.

Type	Spark Ignition
Displacement	244.3 cc
Bore size	72 mm
Stroke	60 mm
Cooling	Liquid cooled
Timing	4 valves – SOHC
Max Power	16.2 kW @ 8250 rpm
Max Torque	20.2 Nm @ 6500 rpm
Weight	36 Kg

This engine has been optimised for the generator set operation modifying some characteristics as inlet and outlet manifold length, valve timing, compression ratio, injection timing, etc.
The electric traction motor and the electric generator will have the specification reported in tab.4. These units has been designed specifically for this application by the Power Electronics and Drivers Research Group of University ROMA TRE, that developed also the voltage booster and the electronic control for both electric machines. As previously explained, the voltage booster is needed in order to match the high fluctuation rate of the ultracapacitor pack voltage with the constant input voltage needed by the traction motor inverter.
The powertrain system in completed by the ultracapacitor pack and the CPU that manages all the system and the APU in particular.

Tab.4. Motor and generator main specifications.

Motor	
Type	synchronous permanent magnet
Nominal Power	8 kW
Peak Power	16 kW
Max speed	3400 rpm
Torque @ 0 rpm	56 Nm
Torque @ 3400 rpm	30 Nm
Peak Torque	62 Nm
Cooling	Liquid cooled
Bus voltage	72 V
Weight	25 Kg
Inverter technology	MOSFET
Generator	
Type	synchronous permanent magnet
Nominal Power	5 kW
Peak Power	8 kW
Max speed	5000 rpm
Peak Torque	20 Nm
Cooling	Liquid cooled
Bus voltage	72 V
Weight	31 Kg
Inverter technology	MOSFET

In order to perform a complete testing of the most advantageous energy flows of the powertrain system, the ultracapacitor pack has been oversized in term of capacity. It could be helpful for the choice of the management strategies of APU; in fact, the increased energy stored allows an higher independency of the requested APU power output from the actual vehicle power demand, so there is the possibility of a more free operation of the i.c. engine and a better research for higher efficiency of the APU (the increase rate of output power can be downsized) [5][6].
Thus considering, the ultracapacitor pack is made up by 4 elements by MAXWELL; the main specification of the single element are reported in tab.5.
The overall rated voltage of the storage system is 64 V and the total capacitance is 125 F, for a weight of 23 kg and a volume of 18.8 litre. Considering a deep of discharge of 50%, the

deliverable energy is 36.4 Wh; the maximum deliverable power is 48 kW.
The CPU dedicated to the hybrid powertrain management is a PC/104 unit with A/D, D/A and CAN BUS cards; the main task to be performed by the CPU is the management of the APU output power.

Tab.5. Ultracapacitor single element spec.

Rated voltage	16.2 V (6 cell 2.7 V each)
Capacitance	500 F
Max energy	3.17 Wh/kg
Max power	5.4 kW/kg
Volume	4.70 litre
Weight	5.75 kg

In order to perform the management task the CPU acquires several parameters on board; in particular, the following parameters are measured:

- Ultracapacitor pack voltage;
- Ultracapacitor pack in/out current;
- i.c. engine RPM:
- throttle position sensor;
- traction motor RPM;
- accelerator pedal position;
- brake pedal position;
- reverse/forward switch position.

Monitoring these parameters, the CPU is able to control the following parameters:

- i.c. engine requested load;
- generator requested load;
- generator requested RPM;
- traction motor requested load;
- regenerative braking mode.

The i.c. engine load can be controlled by the CPU thanks to the installation of a stepper motor that performs a drive-by-wire control of te throttle, not implemented in the original Piaggio throttle linkage.
All the component sizing here reported are resulting from a computer simulation model of the whole vehicle; in tab.6. the expected vehicle performances are reported. Here two different ultracapacitor pack size are compared (overall weight 16 and 23 kg), together with a Li-ion battery solution (28 kg). All the configurations analysed meet the vehicle performances requested.

First of all here can be observed that the smaller ultracapacitor pack is sufficient to achieve the performances obtained with the bigger ultracapacitor pack, confirming that an improving optimisation of the hybrid powertrain will probably reduce the storage pack.
The fuel consumption of the vehicle, calculated over 100 ECE 15 cycles, is adequate for each configuration, demonstrating that the little energy stored in ultracapacitor (in confrontation of Li-ion pack) is still satisfactory for an optimised operation of the powertrain.
Moreover, the full electric range with ultracap is anyway interesting, and it is comparable with full electric range typical of hybrid vehicle on the market.

Tab.6. Expected vehicle performances.

Storage system	li-ion	ultracapacitor	
Storage system weight	28 kg	17 kg	23 kg
Fuel consumpt. 100 ECE da SOC_{max}	2.3 l/100 km	2.3 l/100 km	2.3 l/100 km
Fuel consumpt. 100 ECE da SOC_{min}	2.6 l/100 km	2.3 l/100 km	2.3 l/100 km
Full electric range	17.9 km	1.5 km	2.1 km
Vehicle weight (with 100 kg of cargo mass)	450 kg	438 kg	444 kg
Max climbing rate	24%	24%	24%
Max speed at 7% climbing rate	82 km/h	82 km/h	82 km/h
max speed	90.7 km/h		
max accel. rate	1.9 m/s^2		

In order to test the powertrain on street condition and confer visibility to the project, a specific rolling chassis has been designed and realised by University of Rome “La Sapienza”; it is a simple spaceframe chassis with double whish bone front and rear suspension links (see fig.1).

3 Auxiliary power unit design

One of the most interesting benefit of series hybrid powertrain is the reduction of the speed and load range of operation of the i.c. engine. This characteristic allows two different level of optimization of i.c. engine:

- The speed and load range can be limited to the most efficient zone in term of fuel consumption;
- The i.c. engine can be tuned with specific attention for the limited speed and load range, with less care for the outer zones.

In order to fulfil that task, first of all a simulation model of the original engine has been realised; that model has been then validate with data derived from test on a eddy current dynamometer.
Then the possibility to modify the engine has been analysed, and with a DOE (Design Of Experiment) optimization running over the model, an optimised redesigned engine has been simulated.
The following parameters have been considered for the optimisation analysis:

- Intake valves diameter;
- Exhaust valves diameter;
- Intake CAM height;
- Exhaust CAM height;
- Intake manifold length;
- Compression ratio;
- Exhaust distribution law;
- Intake distribution law;
- Exhaust manifold length.

For each parameter a range of variation has been defined. A total of 75 simulation have been performed. The best result is 232.8 g/kWh obtained at 4000 rpm, full open throttle (85°). That result represent another 5% cut of the fuel consumption in confrontation with the first optimisation result obtained (239 g/kWh).
So, together with the increase of powertrain efficiency due to the hybrid system, an additional step of optimization can be performed working of the engine tuning.
In the first simple step the main engine parameter considered is the compression ratio, and a 5% cut of fuel consumption is possible just increasing the compression ratio to a workable value (12).
In the second step, more intense modifications of the engine have been proposed, in order to achieve another 5% reduction of fuel consumption, reaching 232.8 g/kWh, that is a good result for a small engine (250 cc.)
The increased engine efficiency could be translated to the whole powertrain; the fuel consumptions per km reported in tab.5 have been calculated with a 250 g/kWh cautious value. If a 232 g/kWh will be reached as simulations indicate, the vehicle efficiency could be improved and the 2 litre/100 km goal approached.

4 Control management system

The Urb-e powertrain is managed by a network of CPU's dedicated to the control of the main system components (see fig.2). The communication between CPUs is managed by an open CAN bus.
Each electrical machine, the traction motor and the generator, is equipped with a CPU that controls the inverter and send and receives significant signals over the CAN bus.
The ultracapacitor storage system is equipped with a voltage booster controlled by a CPU, connected to the CAN bus.
The fuel injection of i.c. engine in managed by a

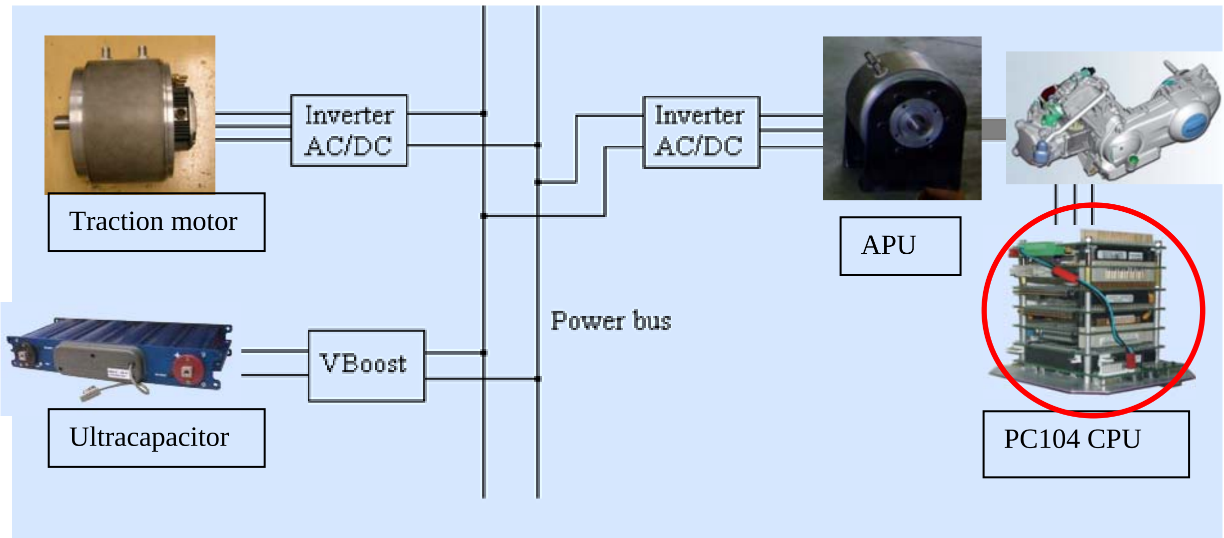

Figure 2. Powertrain CPUs layout.

CPU not connected to the CAN bus, but the throttle position is managed by a ad hoc developed electronic throttle body that is managed by the PC104 supervising CPU, that is connected to the CAN bus.
The CAN bus is utilised to send control signals to each machine or engine and to measure the most important data for testing purpose.
In particular, the following network nodes are available:

Traction Motor
Send: load (%), restore braking (%), speed (rad/s)

Generator Unit
Send: current (A), speed (rad/s)

Ultra Capacitor
Send: link current (A), link voltage (V), ultracapacitor voltage (V)

PC104 Supervisor
Send: load requested to the traction motor (%), current requested to the generator unit (A)

The PC104 Supervisor have to manage the APU power output during the vehicle operations. Reading all the most important data on the CAN Bus, it have to fix the operating point of the APU in term of speed of rotation and throttle position. The APU can operate freely between 1200 and 5000 rpm and 0 to 100% of throttle position (generator and i.c. engine have the same maximum torque); the choice of the current point of operation of the i.c. engine and, thus, of the APU, have to be fixed considering the following targets:

- to avoid overdischarge of ultracapacitor beyond the lower limit of the voltage booster;
- to avoid overcharge of ultracapacitor beyond the upper limit of the voltage booster;
- to assure the satisfactory power to the traction motor;
- to reduce the i.c. engine fuel consumption;
- to allow the regenerative braking.

A control algorithm has been defined in order to achieve all the targets previously described; the control strategy utilises the information available on the CAN bus, in particular ultracapacitor voltage, accelerator pedal position and vehicle speed are the most important parameters for the control.
The control strategy, when the APU requested power is determined, have to manage the throttle position and the speed of rotation in accordance to the requested value of APU power.
A PID control has been implemented in order to control the throttle position and the i.c. engine speed, acting also on the generator requested current. The electronic throttle body is controlled by a separate ECU driven by the PC104 through an analogic channel 0-5V. The generator requested

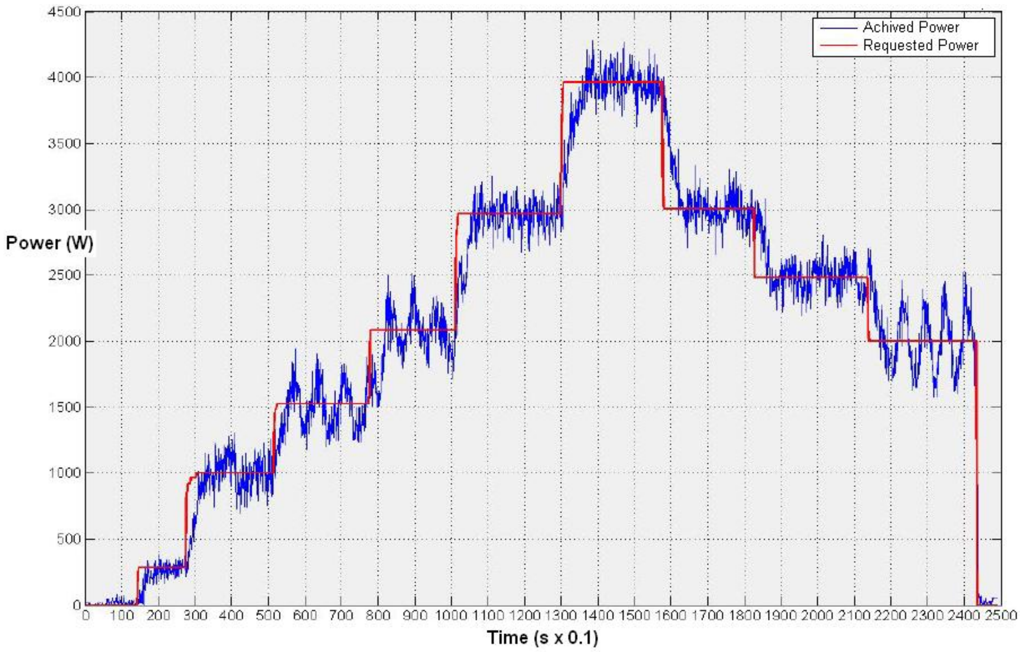

Figure 3. APU: requested and achieved power.

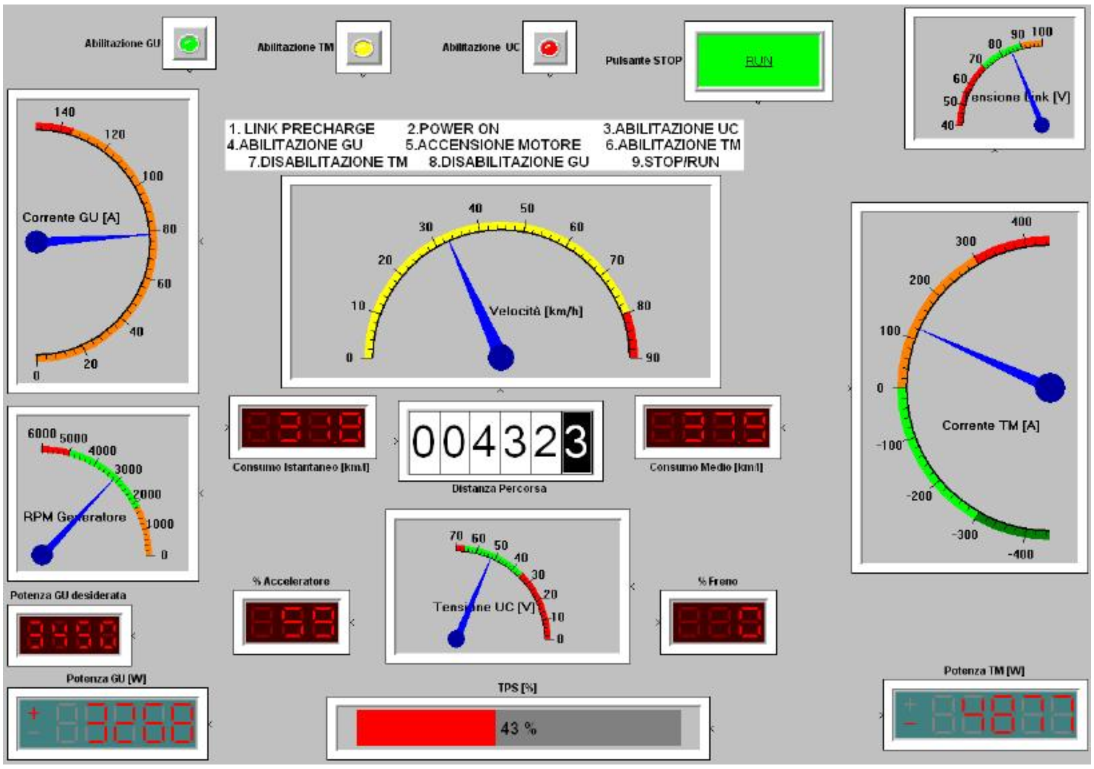

Figure 4. Dial and gauges software panel used for the URB-e tests.

current is communicated by the PC104 to the generator CPU through the CAN bus.

Summing up, the control system is splitted in two different procedures, one that have to decide the desired power output and the desidered rotation speed of the APU, the other that have to drive the APU controls, throttle position and generator current, in order to achieve the desired APU power output in few seconds (2-3 s).

In fig. 3 and example of APU power management is reported. Little ripples around the desired speed values can be observed, due in particular to some errors in the generator current measure.

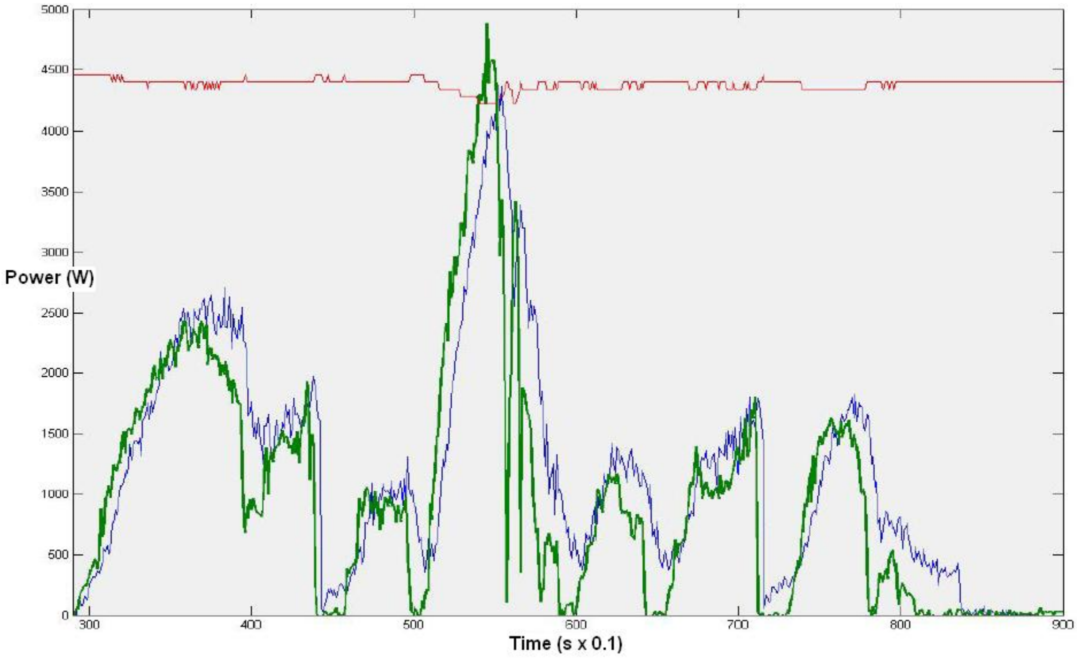

Figure 5. First road test results. Green line: traction motor power; Blue line: APU power outpur; Red line: Ultracapacitor voltage.

5 Urb-e test results

The URB-e prototype has been completed in October 2008 and on February 2009 the APU control system has been tested and the road tests started.

The prototype is equipped with a car computer connected via RS-232 to the PC104 CPU; the car computer is dedicated to implement a digital dial and gauge system (see fig.4) useful to display in real time and to store all the powertrain parameters for off board evaluations. In particular, through the dashboard with a TFT touch screen it is possible to start and stop the powertrain, and it is possible to visualise the APU throttle position and the delivered currents and power. The ultracapacitor SOC and the traction motor operation are also shown.

The first version of the APU power output estimator tested on road is a simple low pass filter over the traction motor power output, integrated by a control on the ultrcapacitor over charge and discharge. Acting on the filter parameters it is possible to adjust the APU responsiveness to the vehicle mission. A large band filter corresponds to a quick response of the APU that follow in short time the traction motor power output, and the storage system is under utilised. A narrow band filter isolates the APU from the traction motor operation, and the ultracapacitor are more deployed.

In fig. 5 some results of that experimentation are represented.

As expected, the ultracapacitor storage system is not used at its best, but this simple road test is useful to verify the APU management procedure.

Figure 6. Damaged rotor permanent magnets.

Unfortunately, during one of these road test, a mechanical problem to the generator is occurred; the rotor has loosen some pieces of two of the permanent magnets, as shown in fig.6.

This problem has been solved now, but unfortunately not in time to present here other road test results. Optimised filter road test results will be reported in the Congress presentation for a better scientific discussion.

6 Conclusions

Urb-e is a project by ENEA developed in collaboration with Sapienza University of Rome and University of Roma Tre.

The first prototype of the Urb-e project is a series hybrid city car, currently under road testing.

The whole electronic management system has been developed by th design team of Sapienza and it is now completely operative.

The most important original result that can be obtained with the Urb-e prototype is the experimental testing of the best management techniques for a series hybrid powertrain with a storage system made up by only ultracapacitor. The first results of this experimentation are here reported.

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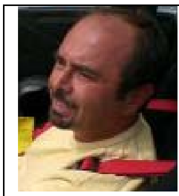

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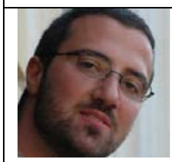

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